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Sensitive Geiger-Muller Counters for Detection of Gamma Rays   38136

Friedman, Herbert   (None)

     Office of Naval Research, Naval Research Lab., Washington, D. D.   M-1886

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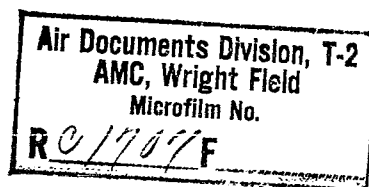June '42   Unclass.   U.S.   Eng.   23   photos, tables, graphs, drwgs

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ATI No. 38136

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NAVAL RESEARCH LABORATORY
REPORT

8 June 1942

SENSITIVE GEIGER-MULLER COUNTERS FOR
DETECTION OF GAMMA RAYS

By Herbert Friedman

Report No. M-1886

UNCLASSIFIED

NAVY DEPARTMENT

Report on

Sensitive Geiger-Muller Counters for

Detection of Gamma Rays

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gm

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ABSTRACT

The various factors determining the efficiency of a gamma ray counter and its applicability as a detector of gamma radiation are evaluated. As an illustration of the practical application of the theory to the construction of an ultra-sensitive counter, such a counter has been built and tested. The results verify the theory and prove that gamma ray counters may be constructed with much greater sensitivity than the simple Geiger-Muller tube counter. In estimating the ultimate range of counters for detection of radium, criteria for "detection" are discussed. For rapid detection, i.e., for measurements covering about one second, it is shown that the above test counter can reliably detect 50 milligrams of radium at 250 feet in air and at almost 6 feet under water.

I. AUTHORIZATION

1. The work described in this report forms part of a program devoted to the development of Geiger-Muller counter technique for measurement of X-ray and gamma ray intensities. The authorization is under the Bureau of Ships Project Order 384/41. Refer to NRL letter N8-12 Radiography, of September 23, 1940 (BuShips file No. NP14/N8 (9-23).

II. STATEMENT OF PROBLEM

2. Questions of the range at which a Geiger-Muller counter can detect a given amount of radium arise not only in the problem of recovering lost radium, but also in considering possible uses of radium as a marker. The distance at which a source of given strength may be detected is dependent on the sensitivity of the counter, the background counting rate, and the speed of measurement. The purpose of this report is (1) to estimate the limits to which the sensitivity may be increased by improved counter design, (2) to investigate generally accepted criteria for what constitutes "detection," as they are affected by counting rate and speed of measurement, and (3) to describe the construction of a counter of superior sensitivity and compare its performance with theoretical predictions.

III. KNOWN FACTS BEARING ON PROBLEM

3. The Geiger-Muller counter is by far the most sensitive of all devices for detection of individual charged particles and quanta of radiation. So great is its internal amplification that a single electron suffices to trigger a flow of charge of as many as ten billion electrons. This triggering electron may enter the counter directly, or appear as an X-ray or gamma ray secondary (photoelectric ejection and Compton effect), or as the product of corpuscular ionization due to energetic charged particles. The common form of G-M counter, Plate I, is simply a cylindrical cathode and a centered anode wire, enclosed in a glass envelope. Normally, the tube is filled with a fraction of an atmosphere of a suitable gas, or mixture of gases, and a potential difference of the order of 1,000 volts is applied to the electrodes. To operate the tube as a G-M counter, the voltage is set to a value somewhat less than is necessary to maintain a self-sustained discharge between the electrodes. All that is then required to trigger a momentary discharge is the passage of some ionizing radiation through the counter. By proper construction of the counter and its associated circuit, a discharge triggered by the absorption of a quantum of radiation

may be quenched very quickly. To determine the intensity of radiation entering the counter, one measures the number of discharge pulses per unit time. (For details of counting action and circuits for counting pulses, see NRL Report M-1800).

IV. THEORETICAL CONSIDERATIONS

A. Theory of the Sensitivity of A Gamma Ray Counter.

4. The electrons that trigger the discharges in a gamma ray counter are ejected from the cathode wall by "Compton Scattering." This process is almost entirely responsible for gamma ray absorption in matter. Only a negligible fraction of the gamma radiation that enters the counter is absorbed in the gaseous volume, but every Compton electron emerging from the cathode triggers a discharge. The efficiency of a gamma ray counter must obviously depend on the wall thickness of the cathode. The Compton electrons are very strongly absorbed in the metal in which they are produced and may be thought of as having a "mean free path" of the order of one or two millimeters. If the cathode is made very thin, all the electrons may succeed in getting out into the gaseous volume of the counter, but the thin wall absorbs so few gamma ray quanta that the number of electrons produced is small to start with. On the other hand, if the cylinder is thick, a much higher percentage of the primary gamma radiation is absorbed, but very few of the electrons produced at depths greater than the "mean free path" can penetrate the distance to the inner surface of the cylinder. The existence of an optimum wall thickness may be shown by a simple calculation (NRL Report M-1800). For this optimum thickness, the calculated efficiency is given by:

$$\text{Efficiency} = \frac{\text{number of counts}}{\text{number of primary quanta}} = \frac{u_1}{u_2} \quad , \quad (1)$$

where u_1 = linear absorption coefficient for gamma rays

u_2 = linear absorption coefficient for electrons

The ratio u_1/u_2 is approximately 0.01 for aluminum and 0.013 for brass. On the average, only one electron is ejected and one count detected, for about 100 incident quanta.

5. The relative efficiencies of counters having different thicknesses of cylinder wall are given in Table I.

TABLE I

Wall thickness	Relative Efficiency
0.5 mm.	.70
1.0 "	.89
2.0 "	.93
3.0 "	.91

Maximum efficiency is obtained for a thickness of about 2 mm.

B. How to Increase Efficiency of Simple Counter.

6. Two steps that may be taken to increase the number of emergent secondary electrons per primary quantum are: (1) increasing the total surface per unit area of the cathode, and (2) increasing the ratio of u_1 to u_2. In the first case, it is possible to increase the surface area of a cylinder of given volume by grooving the surface, or by fashioning the cylinder out of fine wire mesh. When 100 mesh wire is employed, the efficiency is approximately double that of a smooth cylinder. The second means of gaining efficiency is to choose heavier metals for cathode material. With higher atomic weight, the gamma ray absorption coefficient increases more rapidly than the electronic absorption coefficient. A counter with a lead cylinder has been found to be 1.3 times as efficient as one with a copper cylinder[1]

C. Use of a Multiplicity of Counters for High Efficiency.

7. A simple counter with a brass cyliner 1/32 of an inch thick has an efficiency of about 1.2%. If such a counter is used to measure the intensity of a beam of radiation it absorbs about 5% of the incident energy. If the first counter is backed by a similar counter, the second receives 95% of the original intensity and measures it with an efficiency of 1.2%. The combined efficiency of the two counters taken as a unit is therefore about 2.3%. Apparently, all that is necessary to increase the counting efficiency, is to add more counters in line with the measured beam of radiation. However, there is a limit to the number of counters that it is advisable to use since the gain in efficiency per additional tube decreases steadily with the number of tubes.

To illustrate this point, the efficiencies to be expected from combinations of tubes have been tabulated in Table II.

TABLE II

Combinations of Counters Having Cylinder Walls 1/32 of an Inch Thick

No. of Counters	% of original intensity, absorbed	% of original intensity, transmitted	Efficiency in %
5	23.6	76.4	5.0
10	42.8	57.2	8.8
15	55.3	44.7	11.7
20	65.7	34.3	13.9
25	73.1	26.9	15.6

8. It is apparent from Table II that little is to be gained by using more than 25 tubes, since the gain per tube becomes very small. By constructing the cylinders of 100 mesh wire, the efficiencies may be doubled.

9. By reducing the wall thickness of the counter cylinders, the absorption of radiation is diminished but this is more than counterbalanced by the loss in efficiency, as given in Table I.

D. **The Geiger-Muller Counter as a Detector of Gamma Radiation - Statistics of the Counting Process**

10. The electrons that trigger the discharges in a counter arrive at random, and the laws of probability are directly applicable to the counting process. Most important is the relation between the number of counts produced by a given intensity over a given period of time and the precision with which that intensity is measured by the observed counting rate. This relation is expressed by:

$$E_p = 0.67 \ n^{1/2}, \qquad (2)$$

where E_p is the probable error and n is the number of counts. The relative probable error is given by:

$$E_n = 0.67 \ n^{-1/2} \qquad (3)$$

- 4 -

11. In using the counter as a detector of radiation, it is important to consider the error introduced by the natural background rate. This background rate is the number of counts per unit time resulting from radioactive contaminations in the material of which the counter is constructed and the normal rate due to cosmic rays.

12. If there are N_1 counts due to a certain radiation plus the background, and N_2 counts due to the background only, the probable error of the difference, which is the effect of the source being measured, is $0.67 (N_1 + N_2)^{1/2}$. The relative probable error is:

$$\frac{E_p}{N_1 - N_2} = 0.67 \; \frac{(N_1 + N_2)^{1/2}}{(N_1 - N_2)} \; . \qquad (4)$$

From equation (4) it is apparent that the relative probable error decreases with the square root of the counting rate.

13. Before discussing the relative merits of various counters as detectors of radium gamma rays, it is essential to set up criteria for what constitutes detection. Strictly speaking, no counter may be said to be 100% certain of detecting a given source of radiation no matter how strong. There is always some probability of the counter failing to count a single quantum in a finite time interval. To make detection "certain," this probability must be made very small. The relative probable error (equation 4) is a measure of the probability of detection, since the odds against obtaining a deviation greater than the probable error may be evaluated for any probable error, Table III.

TABLE III

Ratio of Deviation to Probable Error	Odds Against Occurrence
2.0	4.64
2.5	9.90
3.0	22.2
3.5	53.8
4.0	142.3
4.5	415.0
5.0	1,341.0
6.0	19,300.0
10.0	6.5×10^{10}

14. In many publications concerned with the detection of radium, the authors have assumed that a good criterion for detection is that the intensity of the source plus background be twice the background rate alone. According to (4), the relative probable error of the measurement of the effect of the source is then given by:

$$\text{relative probable error} = P.E. = 0.67 \frac{(3 N_2)^{1/2}}{N_2} = \frac{.67\sqrt{3}}{\sqrt{N_2}} . \quad (5)$$

15. What does this mean in terms of probability of detecting the radium source? First of all, it must be remembered that while the average background rate is well defined, instantaneous values have a statistical distribution. Positive and negative values of the background rate are equally probable, so that there is a 50% probability of obtaining an indication higher than the average background rate with no radium present. Some criterion must be established for minimizing the possibility of mistaking background fluctuations for counts due to the radium radiation. Suppose, for example, the background count in the measured interval is 25. The probable error of this count is 13.6%. If it is agreed that the odds against mistaking background fluctuation for radium radiation be at least 25 to 1, then the minimum permissible indication constituting "detection" must be (from Table III) about 2.63 times the P. E. of the background count, or 36%. The P. E. of the effect of the source over the background from equation (5) is 24% when $N_1 = 50$, $N_2 = 25$. The maximum permissible relative error of $(N_1 - N_2)$ is 64%, according to the above restriction on background fluctuation. The odds against occurrence of a relative error greater than 64% when the P. E. is 24% are about 27 to 1. To sum up then, when the background count is doubled, making a combined count of 50, the odds in favor of detection are 27 to 1, if the odds are set at 25 to 1 against mistaking a fluctuation of background count for an effect of the source.

16. By increasing the counter sensitivity, incidentally raising the background count from 25 to 100, the odds in favor of detection become 400,000 to 1, if the odds of 25 to 1 are preserved against background fluctuations. Alternatively, the original odds may be maintained for detection at almost twice the original distance in air from source to counter. It is apparent, therefore, that the highest possible counting rate must be sought for in

detection of gamma radiation, even though the background rate increases simultaneously with the counter sensitivity.

17. If a counter is placed in a region of approximately uniform density of radiation, the counting rate is proportional to the area of the cathode. For high sensitivity in the detection of radiation from a distant source it therefore is desirable to build the counter as large as practicable. One of the largest counters described in the literature[2] is diagrammed in Plate (3). A copper tube five feet long with 1/16 inch wall, formed the cathode. About one foot of this length was left to accommodate a Neher-Harper circuit and an additional stage of amplification. The Pyrex bowls which seal the ends were commercial transmitting station lead-in-bowls, with the edges ground to fit inside the six inch tubing. Commercial argon at a pressure of seven centimeters, constituted the gas filling of the counter. The background rate, N_2, was about one hundred counts per second. According to the results of Taft[3] as shown in Plate (2), the background rate, for a counter in air, is doubled at a distance of about 200 feet from a 50 mg. source. The odds in favor of detecting, in one second, the effect of a 50 mg. source at 200 feet from this large counter are 400,000 to 1.

V. EXPERIMENTAL RESULTS

18. Assuming the volume of a counter is restricted to a given size, how may the maximum sensitivity be obtained? From paragraph (7), it is obvious that by filling the given volume with a multiplicity of small diameter counters, efficiencies as high as 40% may be obtained. A counter of this type was built, containing 37 individual counters, connected in parallel. Plates (4) and (5) are scale drawings of cross-sections of this multiple counter. Plates 6, 7, and 8 are photographs showing the construction. The individual counters are of brass tubing, 12 inches long and 5/8 inch in diameter. The wire anodes are supported by mica disks, punched to fit the ends of the brass tubes. To insulate the wire system from the assembly of cylinders, the wires are passed through glass capillary tubing, where they emerge through the mica disks. The entire system is enclosed in a brass cylinder with 1/16 inch wall, closed at the ends by disks of brass, 1/8 inch thick. This brass container acts as common electrode for all the cylinders. The common lead from the wire system is brought out through an isolantite bushing.

19. The total area of cathode surface in the multiple counter is equivalent to that of a simple counter having 4.2 times as large a volume as the multi-cylinder counter. It should therefore behave very similarly to the counter described in paragraph (1). Its measured background rate is 140 counts per second compared to the 100 per second of the 4 foot counter. Much of the difference in background rate may be attributed to the greater length of wire anode.* The maximum number of cylinders across a diameter of the counter is 7. From Table II, the efficiency of seven counters in line is about 7%. Assuming an efficiency of 1% per individual counter, the counting rate to be expected from a 50 milligram source at any distance, may be roughly calculated. Table IV gives the counting rates for various distances in air from a 50 milligram source, determined with a "frequency meter" (see NRL Report M-1800), and the odds in favor of detection when measurements are made for one second. For detection of radiation under water, the corresponding data are given in Table V. These data were computed from the experimental observations shown on Plates 9, 10 and 11.

TABLE V

Distance in air from source to counter (ft.)	Calculated counting rate due to source (Counts per second)	Measured Counting rate (N_1 + N_2) minus background (N_2 = 140/sec.)(Counts per second)	Relative error of difference (N_1 - N_2) (%)	Odds in favor of detecting 50 mg. of radium
∞	0			1/25 to 1
350	26		33.0	1/16 to 1
300	38	40	22.0	12 to 1
250	58	60	16.0	285 to 1
200	106	110	9.7	$> 10^7$ to 1
150	190	210	6.0	
100	460	470	3.6	

*Spurious background counts tend to arise because of sharp points and dust particles on the wire anode. The longer the anode wire, the greater is the probability of obtaining spurious counts.

TABLE VI

Distance in water from source to counter (ft.)	Calculated counting rate due to source (Counts per second)	Measured Counting rate, (N_1 + N_2) minus background (N_2 = 140/sec.)	Relative error of difference (N_1 - N_2) (%)	Odds in favor of detecting 50 mg. of radium
∞	0			1/25 to 1
6	33	30	29.0	5 to 1
5	192	180	6.7	$>10^{12}$ to 1
4	990	750	2.7	

20. From Table V, it appears that the test counter is capable of almost "certainly" detecting 50 milligrams of radium in one second at 250 feet. If the measuring interval is increased to 1000 second, the range is extended considerably. At 1000 feet, the odds in favor of detection then become 11 to 1. Table VI shows that in one second, the counter cannot fail to detect a 50 milligram source at five feet under water, but increasing the distance by only one foot, drops the odds to as little as 5 to 1.

VI. SUMMARY AND CONCLUSIONS

21. A sensitive gamma ray counter has been built to illustrate a design capable of yielding many times the sensitivity of the simple Geiger-Muller tube counter. The measured response of this counter to a 50 milligram source of radium at various distances in air and in water, agrees with theoretical expectations. It is entirely feasible to build such counters many times as large as the model here described and accordingly obtain extremely sensitive detectors of radium.

22. The particular design of sensitive counter discussed in this report is only one of three types described in NRL Report M-1800, all designed according to the basic principle of obtaining maximum cathode surface. Greatest efficiency in a limited volume is obtained with the multiple-deck type counter, but its construction is considerably more complicated than that of the multi-tube counter.

References

(1) Evans, R.D., and Mugele, R.A., R.S.I., 7, 441
      (1936)

(2) Strong, J., "Procedures in Experimental Physics"
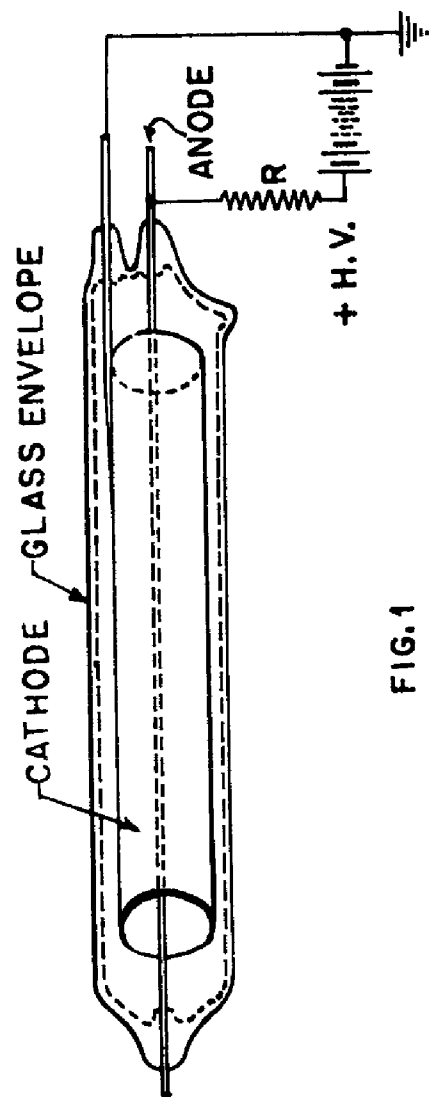   Prentice Hall, 1941
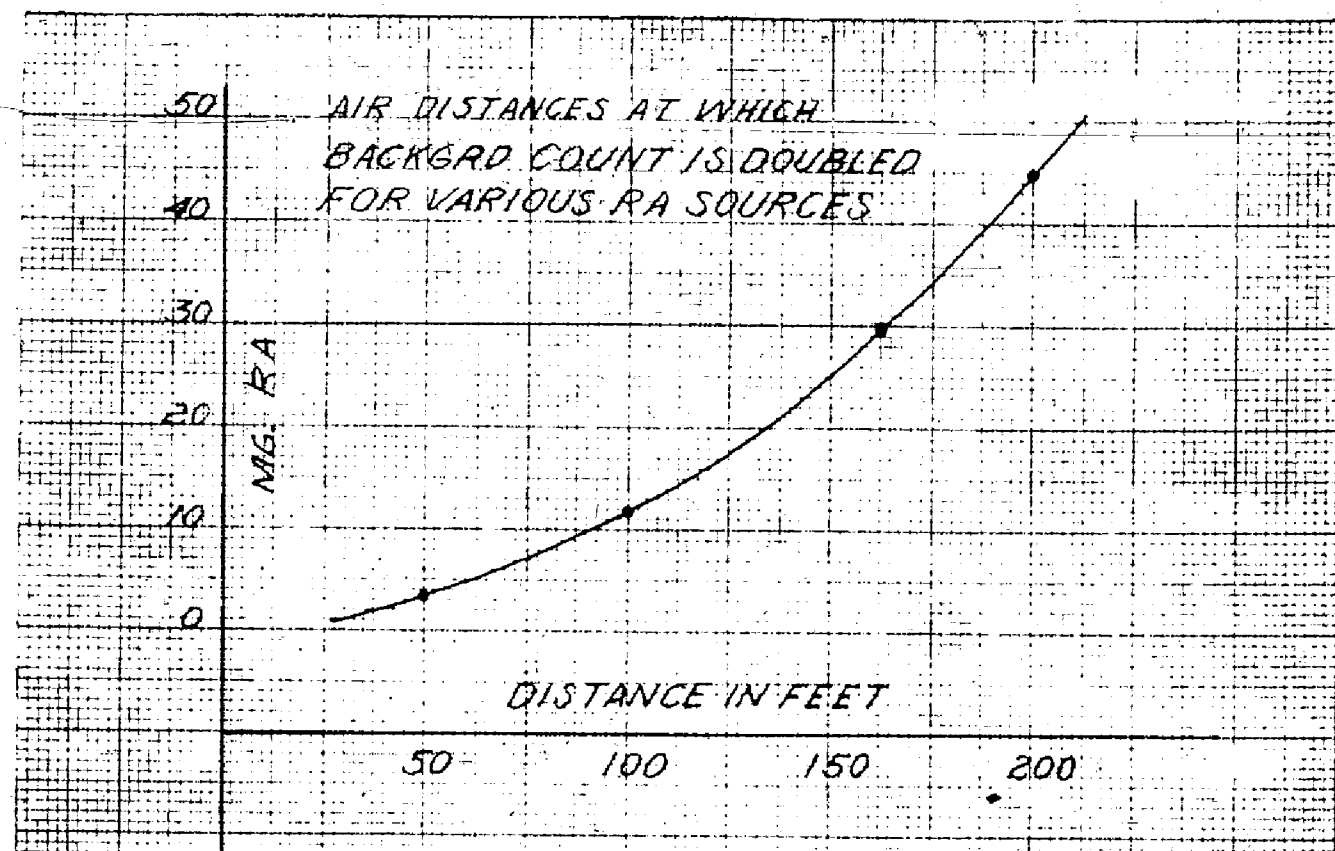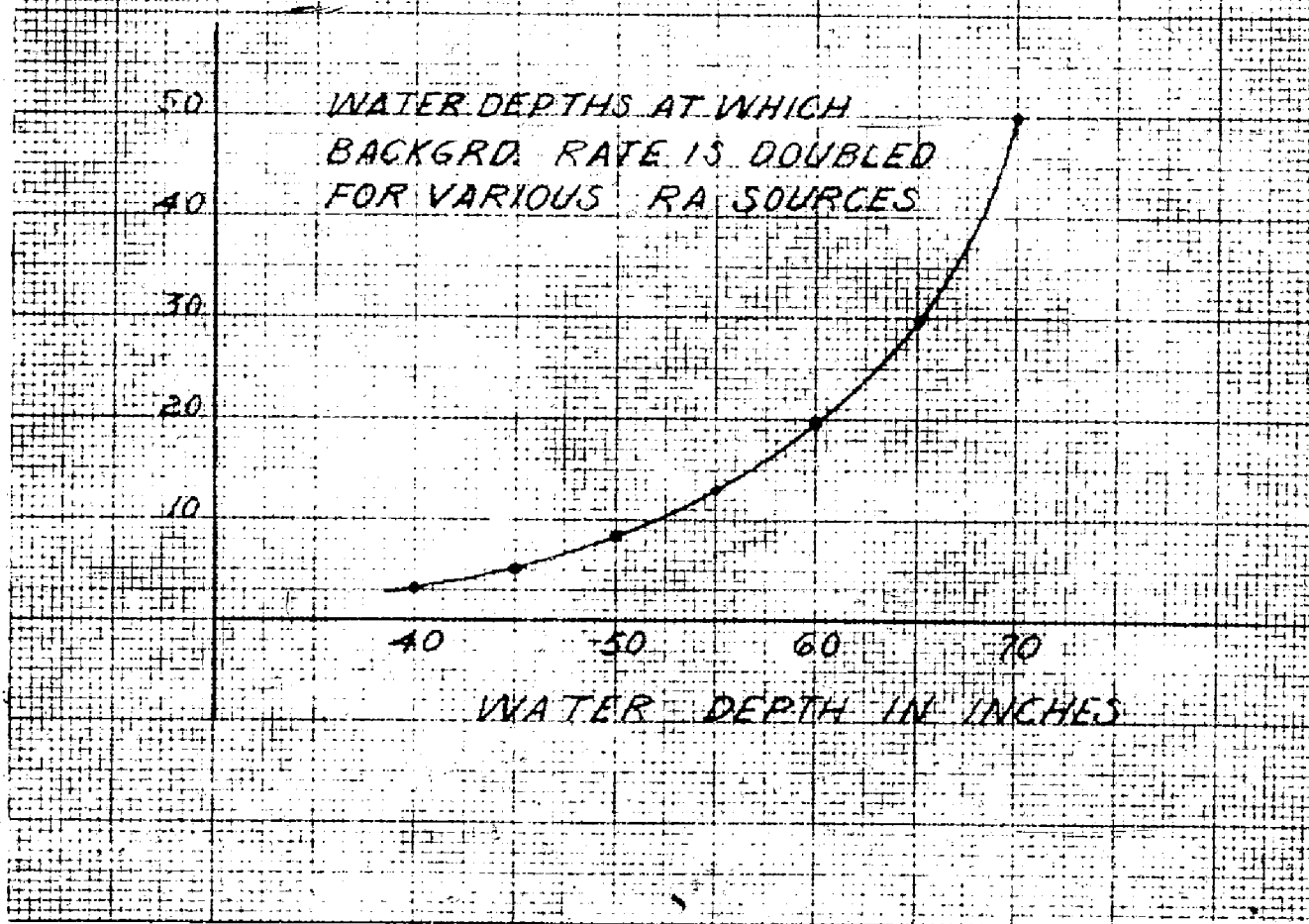
(3) Taft, R.B., Radiology, November 1936

CATHODE
GLASS ENVELOPE
ANODE
R
+ H.V.

FIG.1
GEIGER—MULLER COUNTER

PLATE I

AIR DISTANCES AT WHICH
BACKGRD COUNT IS DOUBLED
FOR VARIOUS RA SOURCES

MG. RA

DISTANCE IN FEET

FIG. 2

WATER DEPTHS AT WHICH
BACKGRD. RATE IS DOUBLED
FOR VARIOUS RA SOURCES

WATER DEPTH IN INCHES

FIG. 3

PLATE 2

sealing wax

Pyrex bowl

brass ring
⅛ thick

20-mil
music wire

6 inches

Argon
(commercial
grade)
7 cm pressure

46 inches

5 feet

16-ga. copper tube

brass ring
⅛ thick
Pyrex
bowl
sealing
wax

Space for
amplifier
unit
(see detail)

sealing
wax

3/16 copper tube
for evacuating
counter,
crimped
and sealed
off with
solder

nuts

spring-brass vane

PLATE 3

$4\frac{3}{8}"$

$5\frac{1}{2}"$

BRASS TUBES $\frac{5}{8}"$ DIA. 12" LG. - 37 REQD

CENTER WIRE (.003") "W"

SPRINGS (.016) PIANO WIRE

GLASS SPACERS $\frac{5}{16}"$ DIA. X $\frac{1}{2}"$ LG.
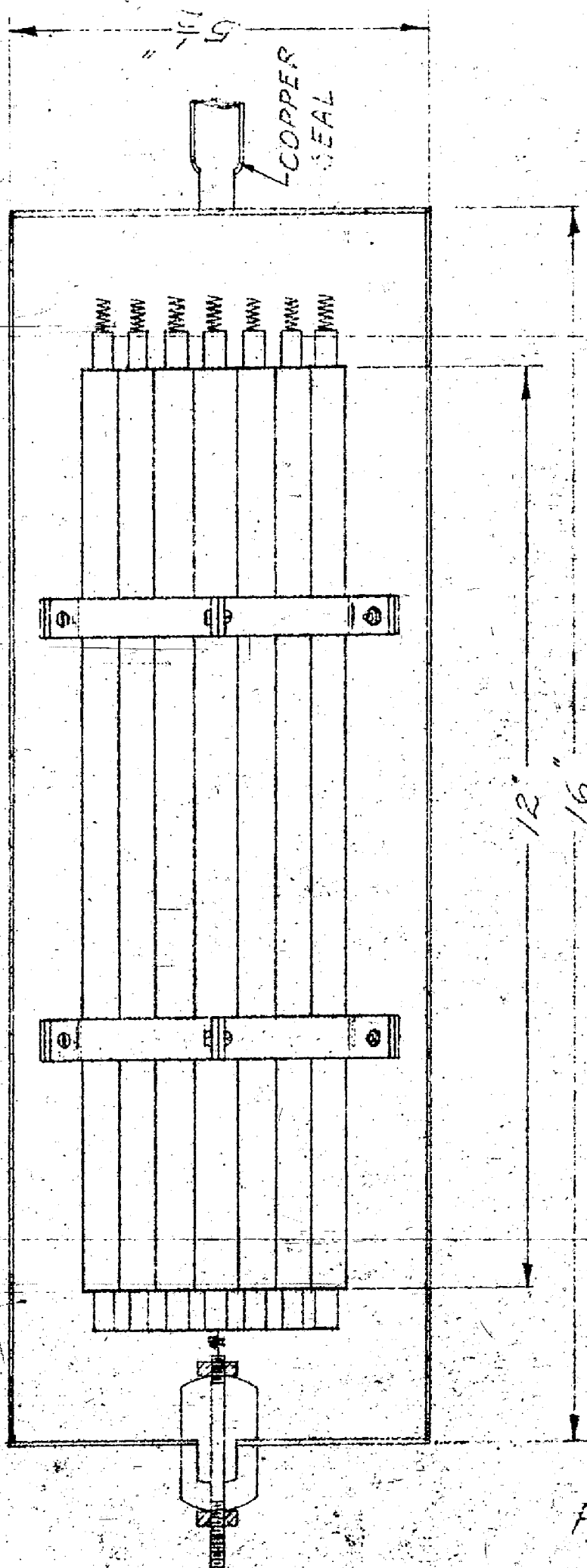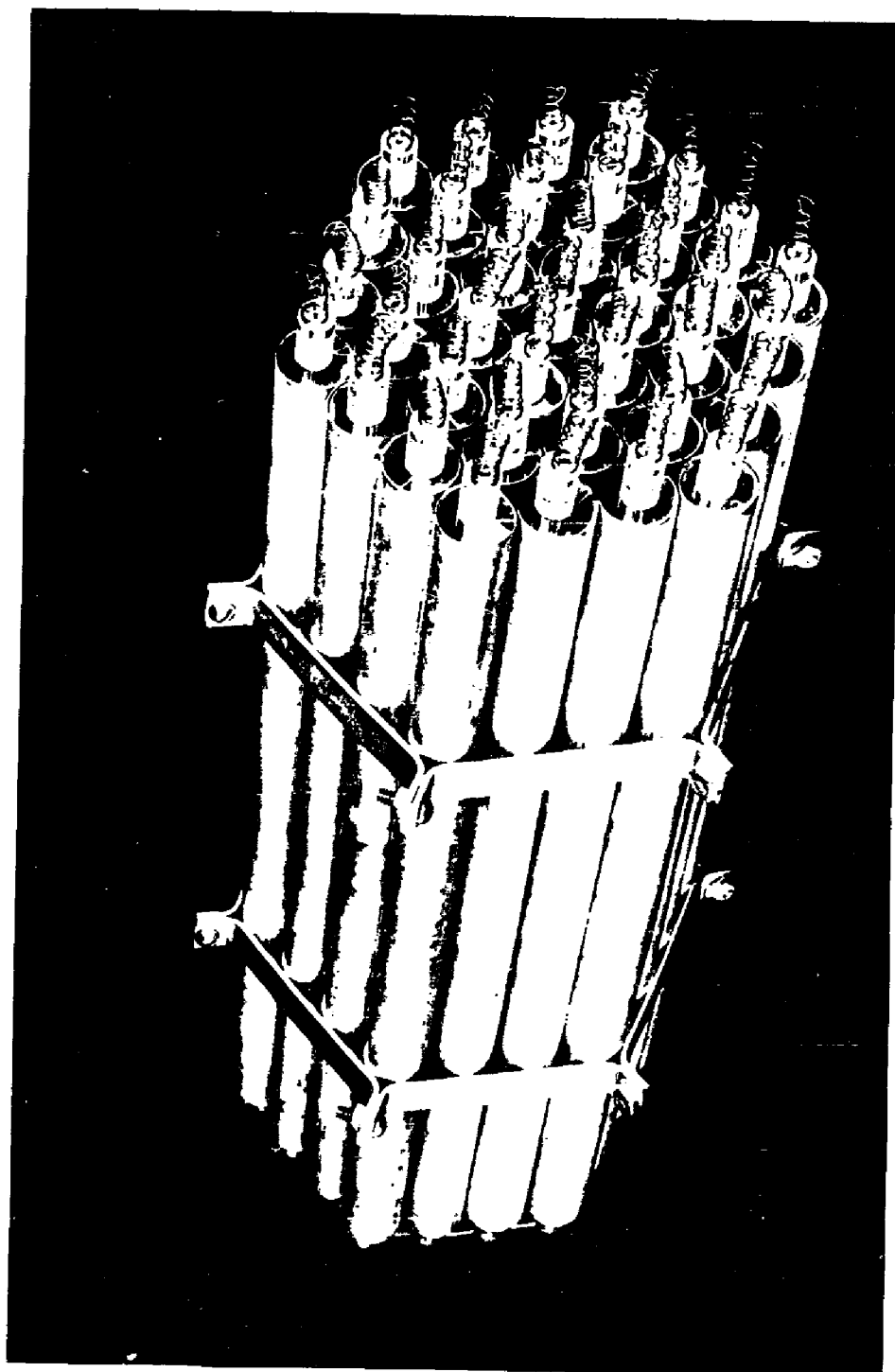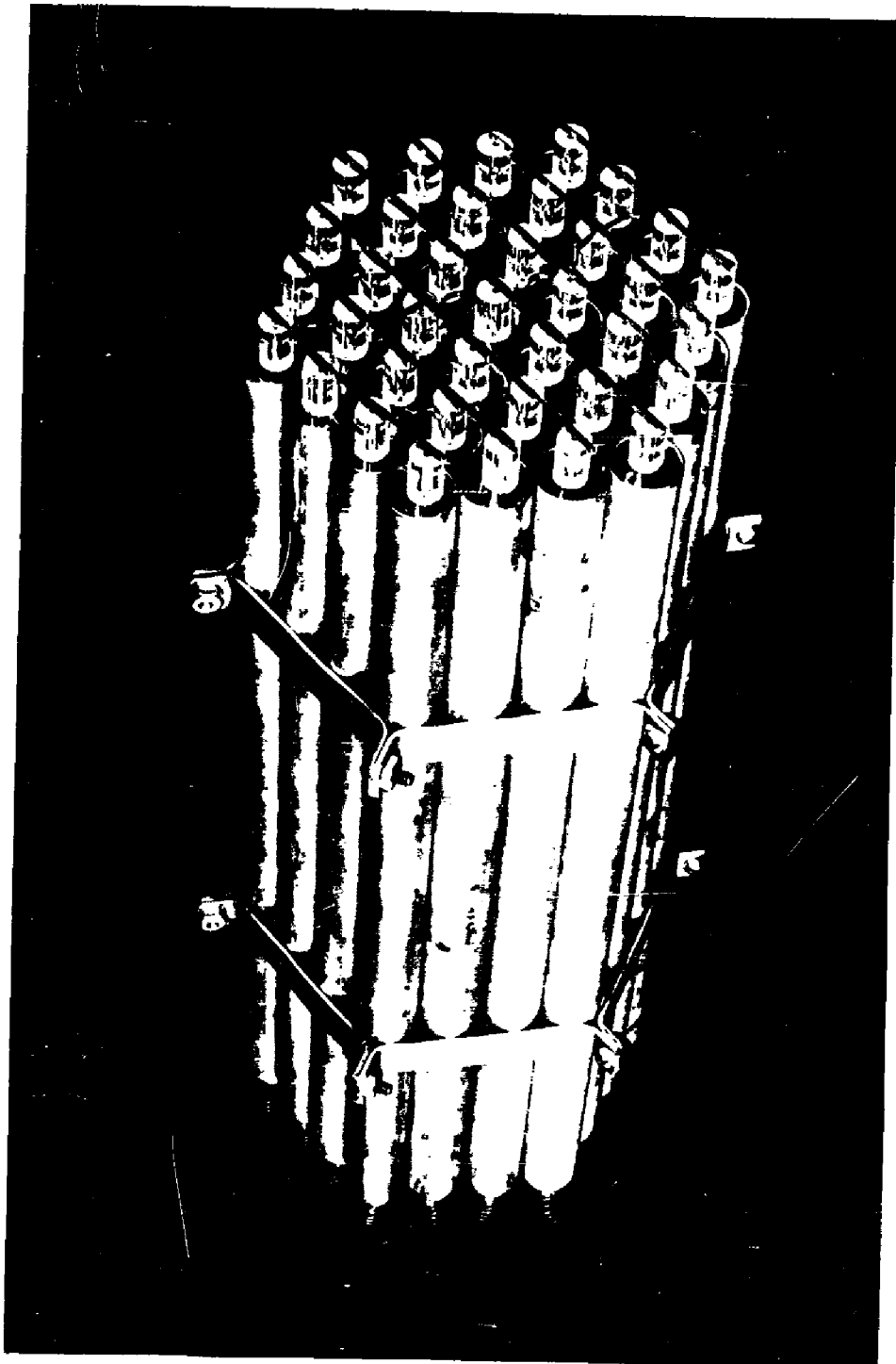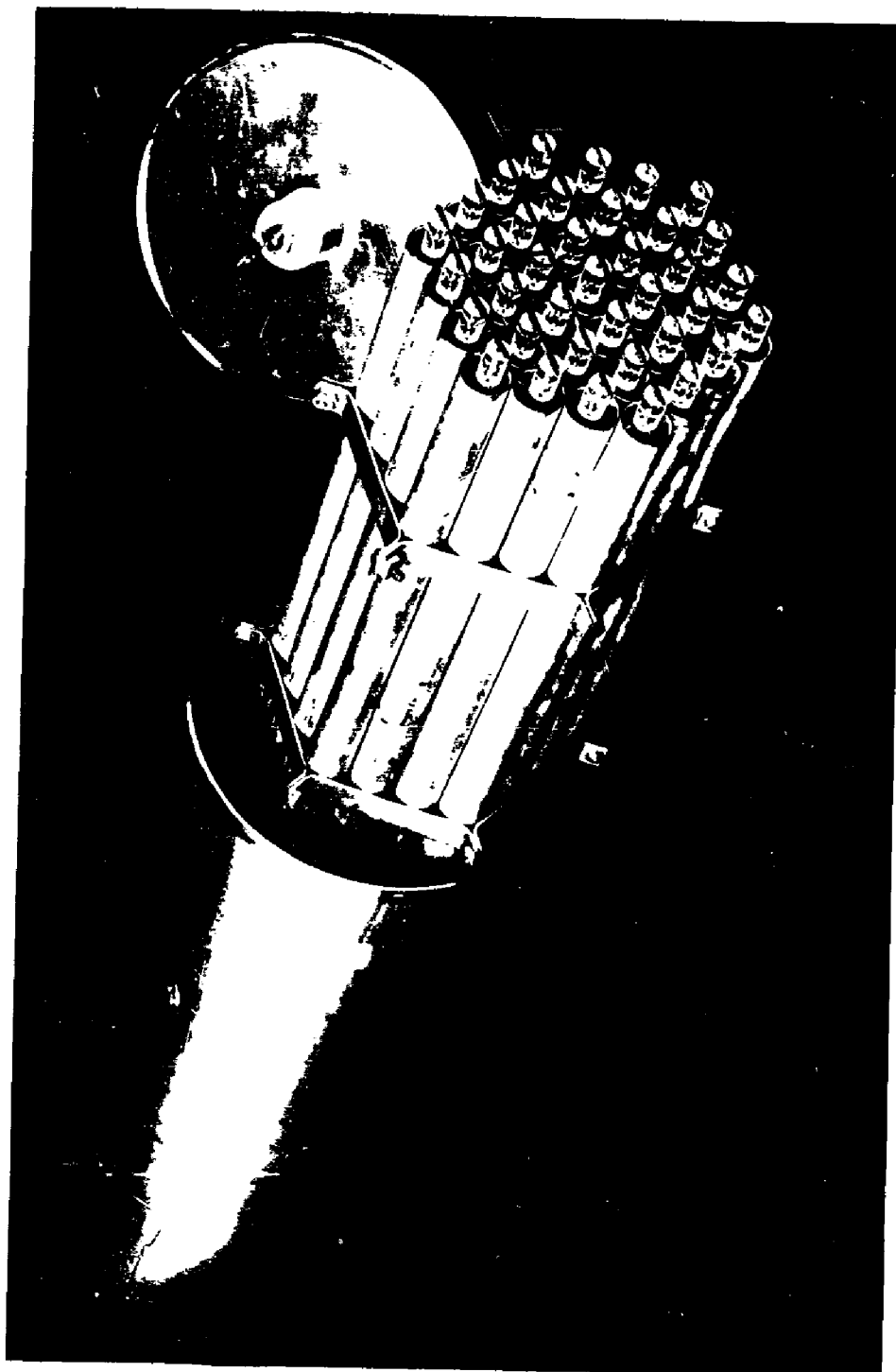
MICA SPACERS $\frac{13}{64}"$

PLATE 4
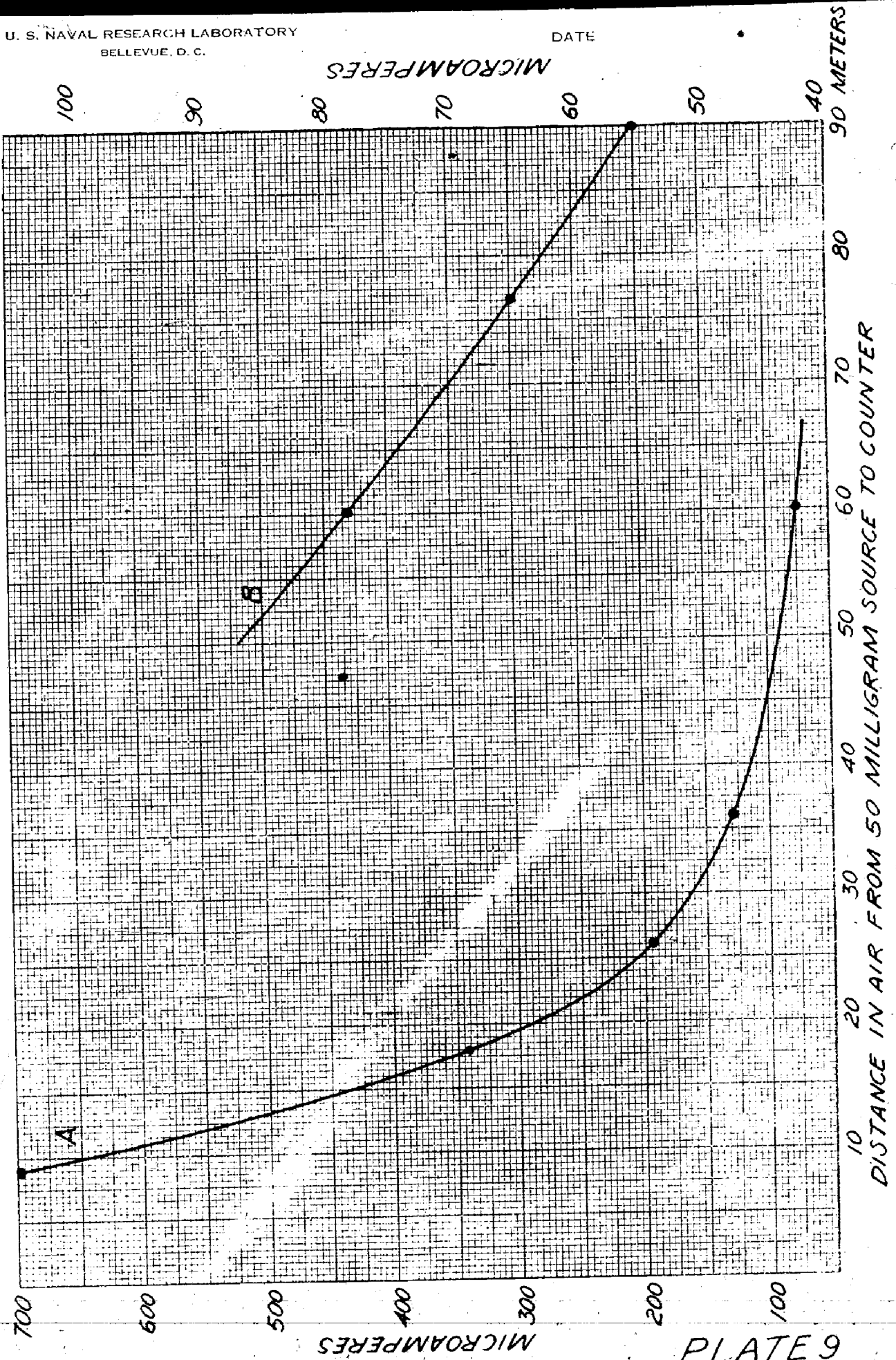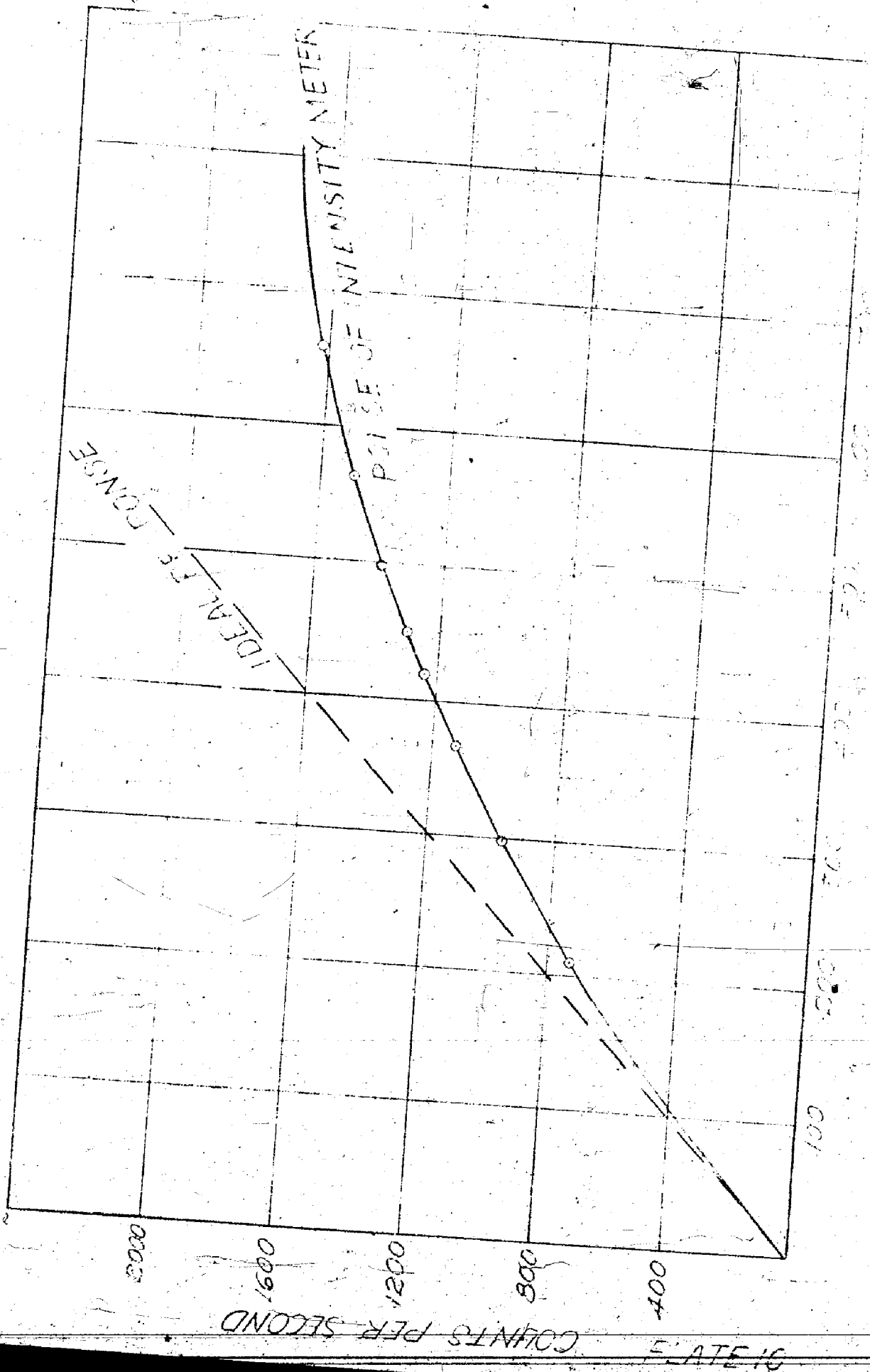
COPPER SEAL

BRASS CAN 16"X 5 5/8"

12"

16"

PLATE 5

PLATE 6

PLATE 7

PLATE 8

MICROAMPERES

90 METERS

DISTANCE IN AIR FROM 50 MILLIGRAM SOURCE TO COUNTER

B

A

MICROAMPERES

PLATE 9

PLATE 16

IDEAL DC CONVERSION INTENSITY METER

IDEAL DC CURVE

COUNTS PER SECOND

U. S. NAVAL RESEARCH LABORATORY
BELLEVUE, D. C.

DATE

MICROAMPERES

DISTANCE UNDER WATER FROM 50 M.G.
SOURCE TO COUNTER
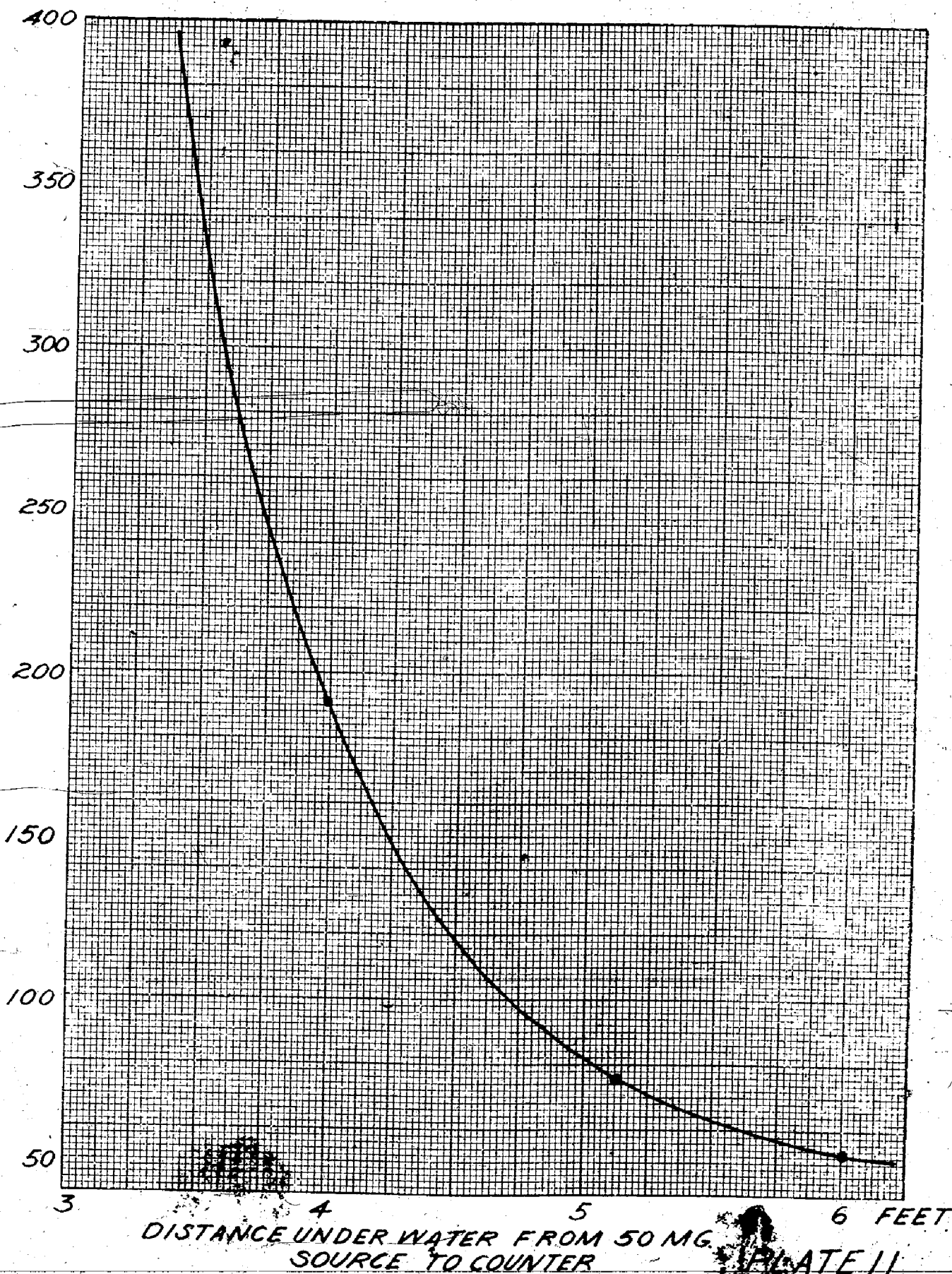
PLATE II

Document Number	**FR-1886**
Order Number	**ATI-38136**
Notes	Dr Gursky code 7600 recommend "Approved for public release" Ser #059 dated Sept 28,1998
Report Classif	Unclassified
Publisher	Naval Research Laboratory
Report Number	NRL-FR-1886
Report Number	NRL-M-1886
Type of Report	Formal Report
Title	Sensitive Geiger-Muller Counters for Detection of Gamma Rays (U)
DATE	06/00/1942
Afflil/author/c	Naval Research Laboratory|p Friedman H
Abstract Classif	U
DIST	A
DISTS	Approved for public release - Distribution is Unlimited
ACT	Accept
Descriptor Class	U
Identifier Class	U
Equipment Class	U
Last Updated	UPSTAIRS |D 1997 03 25
Last Updated	MIT |D 1998 09 30 |T 11:48:39

End of report

TITLE: Sensitive Geiger-Muller Counters for Detection of Gamma Rays

AUTHOR(S): Friedman, Herbert
ORIGINATING AGENCY: Office of Naval Research, Naval Research Lab., Washington, D. C.
PUBLISHED BY: (Same)

ATI- 38136
REVISION (None)
ORIG. AGENCY NO. M-1886
PUBLISHING AGENCY NO. (Same)

DATE	DOC. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
June '42	Unclass.	U.S.	Eng.	23	photos, tables, graphs, drwgs

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DIVISION: Atomic Energy (48)
SECTION: Instruments and Techniques (6)

SUBJECT HEADINGS: Geiger counters (45000); Gamma radiation - Measurement (43096.35)

ATI SHEET NO.: R-48-6-22

Air Documents Division, Intelligence Department
Air Material Command

AIR TECHNICAL INDEX

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